

Dark Energy Cosmology with the Alternative Cosmic Microwave Background Data

Hao Wei*

Department of Physics, Beijing Institute of Technology, Beijing 100081, China

ABSTRACT

Recently, in a series of works by Liu and Li (L&L), they claimed that there exists a timing asynchrony of -25.6 ms between the spacecraft attitude and radiometer output timestamps in the original raw WMAP time-ordered data (TOD). L&L reprocessed the WMAP data while the aforementioned timing asynchrony has been corrected, and they obtained an alternative CMB map in which the quadrupole dropped to nearly zero. In the present work, we try to see the implications to dark energy cosmology if L&L are right. While L&L claimed that there is a bug in the WMAP pipeline which leads to significantly different cosmological parameters, an interesting question naturally arises, namely, how robust is the current dark energy cosmology with respect to systematic errors and bugs? So, in this work, we adopt the alternative CMB data of L&L as a strawman to study the robustness of dark energy predictions.

PACS numbers: 98.80.Es, 95.36.+x, 98.80.Cq, 98.70.Vc

* email address: haowei@bit.edu.cn

I. INTRODUCTION

Dark energy cosmology has been one of the most active fields in astronomy and physics, since the exciting discovery of current accelerated expansion of our universe [1]. The first evidence came from the observation of Type Ia supernovae (SNIa) in 1998 [2]. Five years later, cosmology entered the so-called “precision era” in 2003 when the first year Wilkinson Microwave Anisotropy Probe (WMAP) observations of the cosmic microwave background (CMB) had been released [3]. Up to now, the CMB observation is still a very powerful probe for cosmology, and the CMB data from WMAP mission provide the most important basis.

However, in the passed years, some unusual phenomena have been found from the CMB data released by WMAP team. Remarkably, among these unusual phenomena, it is claimed that there exists a preferred direction in the CMB temperature map (known as the “Axis of Evil” in the literature) [4]. In fact, there are two different approaches to deal with this problem. The first one is to admit that this phenomenon is an observational fact and try to explain it in the cosmological theories (see e.g. [5–7] and references therein). The second approach is to consider instead that this phenomenon might be an artifact due to the observational systematics. For example, in a series of works by Liu and Li (L&L) [8–10], they claimed that there exists a timing asynchrony of -25.6 ms between the spacecraft attitude and radiometer output timestamps in the original raw WMAP time-ordered data (TOD). If one fixed this problem, the most of CMB quadrupole component disappear. It is worth noting that recently their findings has been confirmed by several independent authors (see e.g. [11–13]). In [8], L&L reprocessed the WMAP data while the aforementioned timing asynchrony has been corrected, and they obtained an alternative CMB map in which the quadrupole dropped to nearly zero. In addition, using the alternative CMB data, they constrained the cosmological parameters of the standard flat Λ CDM model, and found that these cosmological parameters have been changed notably. For convenience, we reproduce their main results in Table I. It is easy to see that the fractional matter density $\Omega_{m0} = \Omega_{b0} + \Omega_{c0}$ of L&L [8] is considerably larger than the one of WMAP [14, 15].

Description	Symbol	WMAP [14, 15]	L&L [8]
Hubble constant (km/s/Mpc)	H_0	$71.9^{+2.6}_{-2.7}$	71.0 ± 2.7
Baryon density	Ω_{b0}	0.0441 ± 0.0030	0.052 ± 0.0030
Cold dark matter density	Ω_{c0}	0.214 ± 0.027	0.270 ± 0.027
Dark energy density	$\Omega_{\Lambda 0}$	0.742 ± 0.030	0.678 ± 0.030
Fluc. Ampl. at $8h^{-1}$ Mpc	σ_8	0.796 ± 0.036	0.921 ± 0.036
Scalar spectral index	n_s	$0.963^{+0.014}_{-0.015}$	0.957 ± 0.015
Reionization optical depth	τ	0.087 ± 0.017	0.109 ± 0.017

TABLE I: The cosmological constraints on the standard flat Λ CDM model, reproduced from [8].

To our knowledge, there is still controversy about the findings of L&L in the community. In the present work, we try to be neutral as much as possible. Instead of discussing the detailed data process of WMAP mission (as in the works by L&L [8–10] or other authors [11–13]), in this work we would like to see the implications to dark energy cosmology if L&L are right. While L&L claimed that there is a bug in the WMAP pipeline which leads to significantly different cosmological parameters, an interesting question naturally arises, namely, how robust is the current dark energy cosmology with respect to systematic errors and bugs? So, in this work, we adopt the alternative CMB data of L&L as a strawman to study the robustness of dark energy predictions.

As is well known, using the full CMB data to perform a global fitting consumes a large amount of computation time and power. As a good alternative, one can instead use the shift parameter R from the CMB data, which has been considered extensively in the literature. It is argued that the shift parameter R is model-independent, and it contains the main information of the CMB data [16]. So, in Sec. II we firstly derive the corresponding shift parameter R from the alternative CMB data of L&L [8].

In addition, we briefly introduce the other observational data, such as SNIa and the baryon acoustic oscillation (BAO), which are also used in the present work. In Sec. III, we perform the data analysis by using the cosmological observations introduced in Sec. II. In particular, we discuss the tension between CMB and SNIa in Sec. III A; we study the age problem in dark energy models in Sec. III B; and the cosmological constraints on dark energy models are considered in Sec. III C. Finally, the conclusion and discussions are given in Sec. IV.

II. OBSERVATIONAL DATA

A. Shift parameter R from the alternative CMB data

As mentioned above, using the shift parameter R from the CMB data is a good approach to fit the cosmological models. As is well known, the shift parameter R of the CMB data is defined by [17] (see also [14–16])

$$R \equiv \Omega_{m0}^{1/2} \int_0^{z_*} \frac{d\tilde{z}}{E(\tilde{z})}, \quad (1)$$

where Ω_{m0} is the present fractional energy density of pressureless matter; $E \equiv H/H_0$ in which $H \equiv \dot{a}/a$ is the Hubble parameter; $a = (1+z)^{-1}$ is the scale factor (we have set $a_0 = 1$; the subscript “0” indicates the present value of corresponding quantity; z is the redshift); a dot denotes the derivative with respect to cosmic time t ; the redshift of recombination z_* is given by [18] (see also [14, 15])

$$z_* = 1048 \left[1 + 0.00124 (\Omega_{b0} h^2)^{-0.738} \right] \left[1 + g_1 (\Omega_{m0} h^2)^{g_2} \right], \quad (2)$$

where $\Omega_{m0} = \Omega_{b0} + \Omega_{c0}$, and Ω_{b0} , Ω_{c0} are the present fractional energy densities of baryon and cold dark matter, respectively; h is the Hubble constant H_0 in units of 100 km/s/Mpc; and

$$g_1 = \frac{0.0783 (\Omega_{b0} h^2)^{-0.238}}{1 + 39.5 (\Omega_{b0} h^2)^{0.763}}, \quad g_2 = \frac{0.560}{1 + 21.1 (\Omega_{b0} h^2)^{1.81}}. \quad (3)$$

The shift parameter R relates the angular diameter distance to the last scattering surface, the comoving size of the sound horizon at z_* and the angular scale of the first acoustic peak in CMB power spectrum of temperature fluctuations [16, 17].

In principle, one should obtain z_* and R from the full (alternative) CMB data. However, this is a hard work consuming a large amount of computation time and power. On the other hand, L&L have not published their full alternative CMB data in which the timing asynchrony of -25.6 ms between the spacecraft attitude and radiometer output timestamps in the original raw WMAP time-ordered data (TOD) has been corrected. Therefore, in this work we use instead the Monte Carlo method [19]. We choose the standard flat Λ CDM model to be the fiducial model, since its cosmological parameters have been constrained by both WMAP [14, 15] and L&L [8] (see Table I). We generate the Gaussian distributions for Ω_{b0} , Ω_{c0} and h from their best-fit parameters and the corresponding 1σ uncertainties given in Table I. Then, we randomly sample the parameters Ω_{b0} , Ω_{c0} and h from their corresponding Gaussian distribution for N_{mc} times. For each $\{\Omega_{b0}, \Omega_{c0}, h\}$, we can obtain the corresponding z_* and R from Eqs. (2) and (1), respectively. Finally, we can determine the means and the corresponding 1σ uncertainties for z_* and R from these N_{mc} samples, respectively. Notice that in this work we have done $N_{\text{mc}} = 10^6$ samplings. At first, we check this method by calculating z_* and R from the WMAP data, and find that our results are well consistent with the ones given by WMAP team [14, 15]. Then, we turn to the alternative CMB data of L&L [8], and finally find that the corresponding redshift of recombination z_* is given by

$$z_* = 1088.610 \pm 2.373, \quad (4)$$

and the shift parameter R is given by

$$R = 1.761 \pm 0.014. \quad (5)$$

Obviously, the shift parameter R from L&L's alternative CMB data is fairly larger than the one of WMAP [14, 15]. It is argued that the shift parameter R is model-independent, and it contains the main information of the CMB data [16]. Therefore, in the literature the shift parameter R has been used extensively to constrain cosmological models. For the alternative CMB data of L&L [8], the corresponding χ^2 from the shift parameter R reads

$$\chi_{\text{CMB}}^2 = \left(\frac{R - 1.761}{0.014} \right)^2. \quad (6)$$

B. SNIa and BAO data

In addition to the CMB data, we also consider the observations of SNIa and BAO. The data points of the latest 557 Union2 SNIa compiled in [20] are given in terms of the distance modulus $\mu_{\text{obs}}(z_i)$. On the other hand, the theoretical distance modulus is defined as

$$\mu_{\text{th}}(z_i) \equiv 5 \log_{10} D_L(z_i) + \mu_0, \quad (7)$$

where $\mu_0 \equiv 42.38 - 5 \log_{10} h$ and

$$D_L(z) = (1+z) \int_0^z \frac{d\tilde{z}}{E(\tilde{z}; \mathbf{p})}, \quad (8)$$

in which \mathbf{p} denotes the model parameters. The corresponding χ^2 from the 557 Union2 SNIa reads

$$\chi_{\mu}^2(\mathbf{p}) = \sum_i \frac{[\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i)]^2}{\sigma^2(z_i)}, \quad (9)$$

where σ is the corresponding 1σ error. The parameter μ_0 is a nuisance parameter but it is independent of the data points. One can perform an uniform marginalization over μ_0 . However, there is an alternative way. Following [21, 22, 28], the minimization with respect to μ_0 can be made by expanding the χ_{μ}^2 of Eq. (9) with respect to μ_0 as

$$\chi_{\mu}^2(\mathbf{p}) = \tilde{A} - 2\mu_0 \tilde{B} + \mu_0^2 \tilde{C}, \quad (10)$$

where

$$\begin{aligned} \tilde{A}(\mathbf{p}) &= \sum_i \frac{[\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i; \mu_0 = 0, \mathbf{p})]^2}{\sigma_{\mu_{\text{obs}}}^2(z_i)}, \\ \tilde{B}(\mathbf{p}) &= \sum_i \frac{\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i; \mu_0 = 0, \mathbf{p})}{\sigma_{\mu_{\text{obs}}}^2(z_i)}, \quad \tilde{C} = \sum_i \frac{1}{\sigma_{\mu_{\text{obs}}}^2(z_i)}. \end{aligned}$$

Eq. (10) has a minimum for $\mu_0 = \tilde{B}/\tilde{C}$ at

$$\tilde{\chi}_{\mu}^2(\mathbf{p}) = \tilde{A}(\mathbf{p}) - \frac{\tilde{B}(\mathbf{p})^2}{\tilde{C}}. \quad (11)$$

Since $\chi_{\mu, \text{min}}^2 = \tilde{\chi}_{\mu, \text{min}}^2$ obviously, we can instead minimize $\tilde{\chi}_{\mu}^2$ which is independent of μ_0 . It is worth noting that the corresponding h can be determined by $\mu_0 = \tilde{B}/\tilde{C}$ for the best-fit parameters.

Similar to the case of shift parameter R , one can use the the distance parameter A of the measurement of the BAO peak in the distribution of SDSS luminous red galaxies [23], which is also model-independent and contains the main information of the observation of BAO. The distance parameter A is defined by [23]

$$A \equiv \Omega_{m0}^{1/2} E(z_b)^{-1/3} \left[\frac{1}{z_b} \int_0^{z_b} \frac{d\tilde{z}}{E(\tilde{z})} \right]^{2/3}, \quad (12)$$

where $z_b = 0.35$. In [24], the value of A has been determined to be $0.469 (n_s/0.98)^{-0.35} \pm 0.017$. Here the scalar spectral index n_s is taken to be 0.957 from L&L [8] (see also Table I). The corresponding $\chi^2_{\text{BAO}} = (A - A_{\text{obs}})^2 / \sigma_A^2$.

The best-fit model parameters are determined by minimizing the corresponding χ^2 . As in [25, 26, 76], the 68.3% confidence level (C.L.) is determined by $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\text{min}} \leq 1.0, 2.3$ and 3.53 for $n_p = 1, 2$ and 3 , respectively, where n_p is the number of free model parameters. Similarly, the 95.4% C.L. is determined by $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\text{min}} \leq 4.0, 6.17$ and 8.02 for $n_p = 1, 2$ and 3 , respectively.

Observation	χ^2_{min}	Ω_{m0}	w_0	w_a
SN Ia	541.430	0.420	-0.863	-5.490
SN Ia+A	542.636	0.278	-1.007	-0.105
SN Ia+R	542.523	0.295	-1.021	-0.314
SN Ia+A+R	542.936	0.288	-0.969	-0.529

TABLE II: The χ^2_{min} and the best-fit values of Ω_{m0} , w_0 and w_a for the various observations.

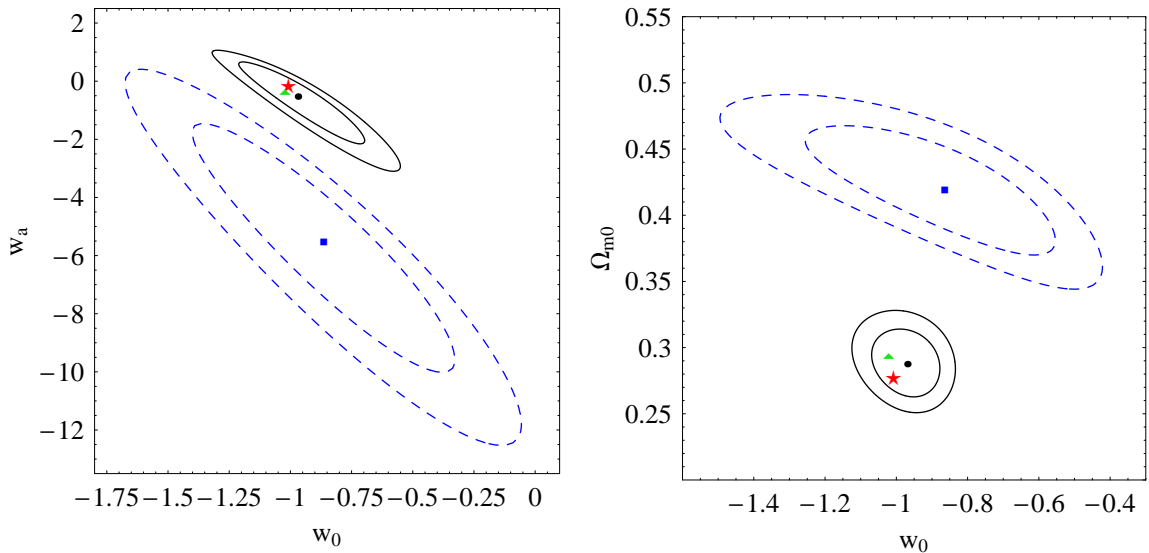


FIG. 1: The 68.3% and 95.4% C.L. contours in the $w_0 - w_a$ plane and the $w_0 - \Omega_{m0}$ plane for the observations of SN Ia alone (blue dashed lines) and SN Ia+A+R (black solid lines). We also show the best-fit values for the observations of SN Ia alone (blue box), SN Ia+A (red star), SN Ia+R (green triangle) and SN Ia+A+R (black point).

III. DATA ANALYSIS

In this section, we perform the data analysis by using the cosmological observations mentioned in the previous section. In particular, we discuss the tension between CMB and SN Ia in Sec. III A; we study the age problem in dark energy models in Sec. III B; and the cosmological constraints on dark energy models are considered in Sec. III C.

A. Tension between CMB and SN Ia

There is a long history of the tension between CMB and SN Ia. In [27, 28], the Gold04 SN Ia dataset [29] has been shown to be in 2σ tension with the SNLS SN Ia dataset [30] and the WMAP observations.

Although the Gold04 sample was updated to Gold06 [31] several years later, the tension still persisted. In [32], the tension and systematics in the Gold06 SNIa dataset has been investigated in great detail. Later, the number of SNIa has been significantly increased to $300 \sim 400$ when the Union [33] and Constitution [34] SNIa datasets have been released. Subsequently, in [35] it is found that there is still significant tension between the WMAP CMB data and the Union/Constitution SNIa datasets. The latest SNIa dataset is the Union2 compiled in [20], which is an updated version of Union. However, in [36, 37] it is found that the tension between the WMAP CMB data and the Union2 SNIa dataset still persisted.

Obviously, the tension comes from both sides: CMB and SNIa. In [32, 35–37], the authors mainly concentrated in SNIa datasets, and tried to find the outliers responsible for the tension. However, from the works by L&L [8–10], we become aware of the possible systematics in the CMB data. So, it is natural to see whether the alternative CMB data of L&L [8] can alleviate the tension.

In this subsection, we follow the discussions in [35], and consider the familiar Chevallier-Polarski-Linder (CPL) model [38], in which the equation-of-state parameter (EoS) of dark energy is parameterized as

$$w_{de} = w_0 + w_a(1 - a) = w_0 + w_a \frac{z}{1+z}, \quad (13)$$

where w_0 and w_a are constants. As is well known, the corresponding $E(z)$ is given by [19, 39–41, 71]

$$E(z) = \left[\Omega_{m0}(1+z)^3 + (1 - \Omega_{m0})(1+z)^{3(1+w_0+w_a)} \exp\left(-\frac{3w_az}{1+z}\right) \right]^{1/2}. \quad (14)$$

Here, we consider the shift parameter R from the alternative CMB data of L&L [8], the latest Union2 SNIa dataset [20], and the distance parameter A [24] with n_s from L&L [8]. We fit the CPL model to the observations of SNIa alone, SNIa+ A , SNIa+ R , and SNIa+ $A+R$, respectively. The best-fit values are presented in Table II. In Fig. 1, we also present the 68.3% and 95.4% C.L. contours in the $w_0 - w_a$ plane and the $w_0 - \Omega_{m0}$ plane. From Fig. 1, we find that there is still tension (beyond 2σ) between the alternative CMB data of L&L [8] and the latest Union2 SNIa dataset [20]. However, when we compare Fig. 1 and Table II of the present work with Figs. 1, 2 and Tables I, II of [35], it is easy to see that the tension has been alleviated to some extent in fact. The alleviation mainly comes from two sides: the best-fit Ω_{m0} for L&L's alternative CMB data is increased, whereas the best-fit Ω_{m0} for the Union2 SNIa dataset is decreased. It is worth noting that the contribution to the alleviation from Union2 SNIa dataset is larger than the one from L&L's alternative CMB data [8].

B. Age problem

In history, the age problem played an important role in the cosmology for many times (see e.g. [42] for a brief review). The main idea is very simple: the universe cannot be younger than its constituents. For example, the matter-dominated Friedmann-Robertson-Walker (FRW) universe can be ruled out because its age is smaller than the ages inferred from old globular clusters. The age problem becomes even more serious when we consider the age of the universe at high redshift (rather than today, $z = 0$). So far, there are some old high redshift objects (OHROs) been discovered. For instance, the 3.5 Gyr old galaxy LBDS 53W091 at redshift $z = 1.55$ [43], the 4.0 Gyr old galaxy LBDS 53W069 at redshift $z = 1.43$ [44], the 4.0 Gyr old radio galaxy 3C 65 at $z = 1.175$ [45], and the high redshift quasar B1422+231 at $z = 3.62$ whose best-fit age is 1.5 Gyr with a lower bound of 1.3 Gyr [46]. In addition, the old quasar APM 08279+5255 at $z = 3.91$ is also used extensively, whose age is estimated to be 2.0–3.0 Gyr [47, 48]. To assure the robustness of our analysis, we use the most conservative lower age estimate 2.0 Gyr for the old quasar APM 08279+5255 at $z = 3.91$ [47, 48], and the lower age estimate 1.3 Gyr for the high redshift quasar B1422+231 at $z = 3.62$ [46]. In the literature, there are many works on the age problem in the dark energy models, see e.g. [42, 49–55] and references therein.

In this subsection, we would like to consider the age problems in the flat Λ CDM model and the holographic dark energy (HDE) model, which have been discussed in the literature by using the earlier observational data (see e.g. [42, 50, 51, 54]). Of course, our main goal is to see whether the age problem can be alleviated with the alternative CMB data of L&L [8].

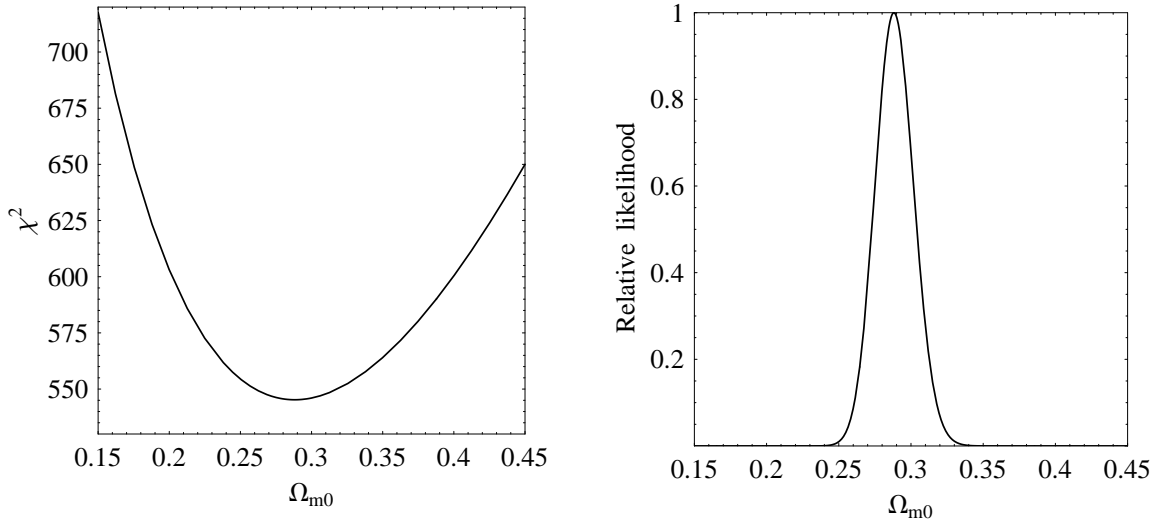


FIG. 2: The χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ as functions of Ω_{m0} for the Λ CDM model.

Description	Ω_{m0}	$S(3.91)$	$S(1.43)$	$S(1.55)$	$S(1.175)$	$S(3.62)$
best fit	0.288	0.799	1.120	1.195	1.310	1.345
1 σ lower bound	0.275	0.817	1.144	1.221	1.337	1.376
1 σ upper bound	0.302	0.781	1.097	1.170	1.283	1.315
2 σ lower bound	0.263	0.836	1.169	1.248	1.366	1.408
2 σ upper bound	0.316	0.763	1.074	1.145	1.257	1.286

TABLE III: The ratio $S(z) \equiv T_z(z)/T_{obj}$ at $z = 3.91, 1.43, 1.55, 1.175$ and 3.62 , for various model parameters Ω_{m0} (within 2σ uncertainty) of the Λ CDM model (the corresponding $h = 0.696$).

1. Age problem in the Λ CDM model

The age of our universe at redshift z is given by [42, 50, 54]

$$t(z) = \int_z^\infty \frac{d\tilde{z}}{(1+\tilde{z})H(\tilde{z})}. \quad (15)$$

It is convenient to introduce the so-called dimensionless age parameter [50, 54]

$$T_z(z) \equiv H_0 t(z) = \int_z^\infty \frac{d\tilde{z}}{(1+\tilde{z})E(\tilde{z})}. \quad (16)$$

At any redshift, the age of our universe should be larger than, at least equal to, the age of the OHRO, namely

$$T_z(z) \geq T_{obj} \equiv H_0 t_{obj}, \quad \text{or equivalently,} \quad S(z) \equiv T_z(z)/T_{obj} \geq 1, \quad (17)$$

where t_{obj} is the age of the OHRO. It is worth noting that from Eq. (16), $T_z(z)$ is independent of the Hubble constant H_0 . On the other hand, from Eqs. (17), T_{obj} is proportional to the Hubble constant H_0 . The lower H_0 , the smaller T_{obj} is.

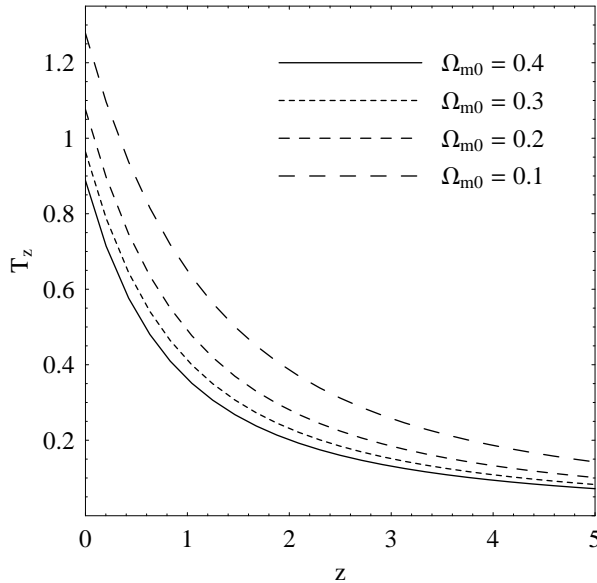


FIG. 3: The dimensionless age parameter T_z as a function of redshift z for various Ω_{m0} in the Λ CDM model.

As is well known, for the flat Λ CDM model,

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + (1 - \Omega_{m0})}. \quad (18)$$

It is easy to obtain the total $\chi^2 = \tilde{\chi}_\mu^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$ as a function of the single model parameter Ω_{m0} for the Λ CDM model, by using the combined observations of the shift parameter R from the alternative CMB data of L&L [8], the latest Union2 SNIa dataset [20], and the distance parameter A [24] with n_s from L&L [8]. We present the corresponding χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ in Fig. 2. The best fit has $\chi_{\text{min}}^2 = 545.239$, whereas the best-fit parameter is $\Omega_{m0} = 0.288^{+0.013}_{-0.013}$ (with 1σ uncertainty) $^{+0.027}_{-0.026}$ (with 2σ uncertainty). The corresponding $h = 0.696$ for the best fit. It is worth noting that although the best-fit Ω_{m0} is smaller than the one from the alternative CMB data of L&L alone [8] (see also Table I) due to the influence of SNIa and BAO, it is still larger than the one from WMAP alone [14, 15] (see also Table I) and the one from WMAP+SNIa+BAO [14, 15].

In Table III, we present the ratio $S(z) \equiv T_z(z)/T_{obj}$ at $z = 3.91, 1.43, 1.55, 1.175$ and 3.62 , for various model parameters Ω_{m0} (within 2σ uncertainty) of the Λ CDM model. Obviously, $T_z(z) > T_{obj}$ holds at $z = 1.43, 1.55, 1.175$ and 3.62 , whereas $T_z(z) < T_{obj}$ at $z = 3.91$. So, the old quasar APM 08279+5255 at $z = 3.91$ cannot be accommodated (beyond 2σ). The age problem still exists in the Λ CDM model, even when the alternative CMB data of L&L [8] has been taken into account.

Let us have a closer observation. As mentioned above, the alternative CMB data of L&L [8] favor a larger Ω_{m0} (this point has also been mentioned by L&L themselves [8]). So, it is natural to see how the model parameter Ω_{m0} affects the age of our universe at redshift z . In Fig. 3, we present the dimensionless age parameter T_z as a function of redshift z for various Ω_{m0} in the Λ CDM model (notice that from Eq. (16), $T_z(z)$ is independent of the Hubble constant H_0). It is easy to see that at any redshift z , the larger Ω_{m0} , the smaller age is. Therefore, the age problem becomes even worse in the Λ CDM model, since the alternative CMB data of L&L [8] favor a larger Ω_{m0} .

2. Age problem in the HDE model

Previously, in [54], the age problem in the HDE model has been discussed in great detail. Here we would like to see whether the age problem can be alleviated with the alternative CMB data of L&L [8].

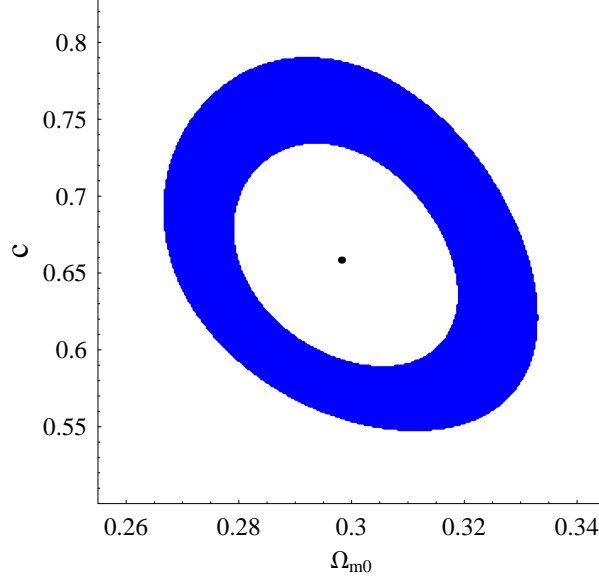


FIG. 4: The 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - c$ parameter space for the HDE model. The best-fit parameters are also indicated by a black solid point.

The HDE model [56, 57] was proposed from the holographic principle [58] in the string theory. HDE is now an interesting candidate of dark energy, which has been studied extensively in the literature. The energy density of HDE reads [57] (see also e.g. [54, 59, 60])

$$\rho_{\Lambda} = 3c^2 m_p^2 L^{-2}, \quad (19)$$

where the numerical constant $3c^2$ is introduced for convenience, and $m_p \equiv (8\pi G)^{-1/2}$ is the reduced Planck mass. In [57], L has been chosen to be the future event horizon

$$R_h = a \int_t^{\infty} \frac{d\tilde{t}}{a} = a \int_a^{\infty} \frac{d\tilde{a}}{H\tilde{a}^2}. \quad (20)$$

From Eqs. (19), (20), and the energy conservation equation $\dot{\rho}_{\Lambda} + 3H\rho_{\Lambda}(1 + w_{\Lambda}) = 0$, it is easy to find that (see e.g. [54, 57, 59, 60])

$$\frac{d\Omega_{\Lambda}}{dz} = -(1+z)^{-1}\Omega_{\Lambda}(1 - \Omega_{\Lambda}) \left(1 + \frac{2}{c}\sqrt{\Omega_{\Lambda}}\right), \quad (21)$$

where Ω_{Λ} is the fractional energy density of HDE. From the Friedmann equation $H^2 = (\rho_m + \rho_{\Lambda}) / (3m_p^2)$, we have

$$E(z) = \left[\frac{\Omega_{m0}(1+z)^3}{1 - \Omega_{\Lambda}(z)} \right]^{1/2}. \quad (22)$$

There are 2 independent model parameters, namely Ω_{m0} and c . One can obtain $\Omega_{\Lambda}(z)$ by solving the differential equation (21) with the initial condition $\Omega_{\Lambda}(z=0) = 1 - \Omega_{m0}$. Substituting $\Omega_{\Lambda}(z)$ into Eq. (22), we can find the corresponding $E(z)$ and then the total $\chi^2 = \tilde{\chi}_{\mu}^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$. By minimizing the total χ^2 , we find the best-fit parameters $\Omega_{m0} = 0.298$ and $c = 0.658$, while $\chi_{\text{min}}^2 = 546.628$. The corresponding $h = 0.703$ for the best fit. In Fig. 4, we present the corresponding 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - c$ parameter space for the HDE model. Comparing with the results of [59, 60], it is easy to see that Ω_{m0} becomes larger, whereas c becomes smaller. Note that $c < 1$ within 2σ region, the EoS of HDE can be less than -1 [61].

Description	(Ω_{m0}, c)	$S(3.91)$	$S(1.43)$	$S(1.55)$	$S(1.175)$	$S(3.62)$
best fit	(0.298, 0.658)	0.771	1.079	1.151	1.263	1.298
1 σ left edge	(0.279, 0.668)	0.797	1.112	1.187	1.301	1.341
1 σ right edge	(0.319, 0.642)	0.746	1.046	1.116	1.226	1.257
1 σ bottom edge	(0.303, 0.589)	0.766	1.076	1.147	1.261	1.290
1 σ top edge	(0.296, 0.734)	0.772	1.076	1.148	1.259	1.300
2 σ left edge	(0.267, 0.678)	0.814	1.135	1.211	1.327	1.370
2 σ right edge	(0.333, 0.622)	0.731	1.027	1.095	1.204	1.231
2 σ bottom edge	(0.308, 0.548)	0.761	1.070	1.141	1.255	1.281
2 σ top edge	(0.294, 0.789)	0.774	1.075	1.148	1.257	1.302

TABLE IV: The ratio $S(z) \equiv T_z(z)/T_{obj}$ at $z = 3.91, 1.43, 1.55, 1.175$ and 3.62 , for various model parameters (Ω_{m0}, c) (within 2σ uncertainty) of the HDE model (the corresponding $h = 0.703$).

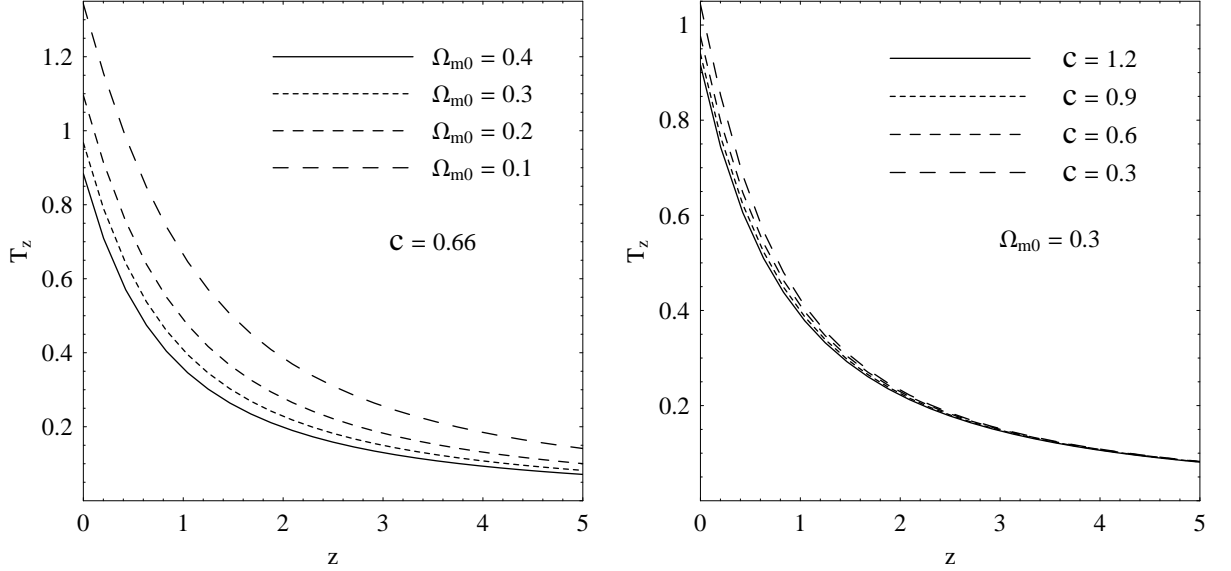


FIG. 5: The dimensionless age parameter T_z as a function of redshift z for various Ω_{m0} and c in the HDE model.

In Table IV, we present the ratio $S(z) \equiv T_z(z)/T_{obj}$ at $z = 3.91, 1.43, 1.55, 1.175$ and 3.62 , for various model parameters (Ω_{m0}, c) (within 2σ uncertainty) of the HDE model. Obviously, $T_z(z) > T_{obj}$ holds at $z = 1.43, 1.55, 1.175$ and 3.62 , whereas $T_z(z) < T_{obj}$ at $z = 3.91$. So, the old quasar APM 08279+5255 at $z = 3.91$ cannot be accommodated (beyond 2σ). The age problem still exists in the HDE model, even when the alternative CMB data of L&L [8] has been taken into account. Further, comparing with the results in [54], it is easy to find that actually the age problem becomes even worse in the HDE model.

Again, we would like to see how the model parameters Ω_{m0} and c affect the age of our universe at redshift z . In Fig. 5, we present the dimensionless age parameter T_z as a function of redshift z for various Ω_{m0} and c in the HDE model (notice that from Eq. (16), $T_z(z)$ is independent of the Hubble constant H_0). It is easy to see that at any redshift z , for a fixed c , the larger Ω_{m0} , the smaller age is; on the other hand, for a fixed Ω_{m0} , the larger c , the smaller age is. However, from Fig. 5, we also find that the influence to the age from Ω_{m0} is significantly stronger than the one from c . As mentioned above, the alternative CMB data of L&L [8] favor a larger Ω_{m0} and a smaller c . Therefore, it is not surprising to find that the age problem becomes even worse in the HDE model.

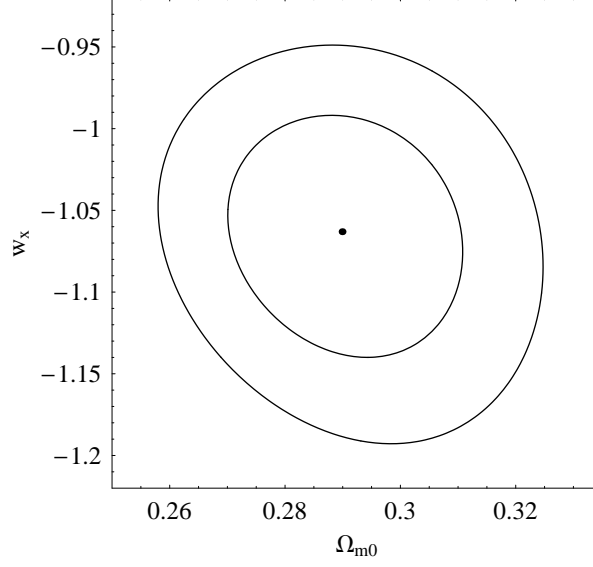


FIG. 6: The 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - w_x$ parameter space for the XCDM model. The best-fit parameters are also indicated by a black solid point.

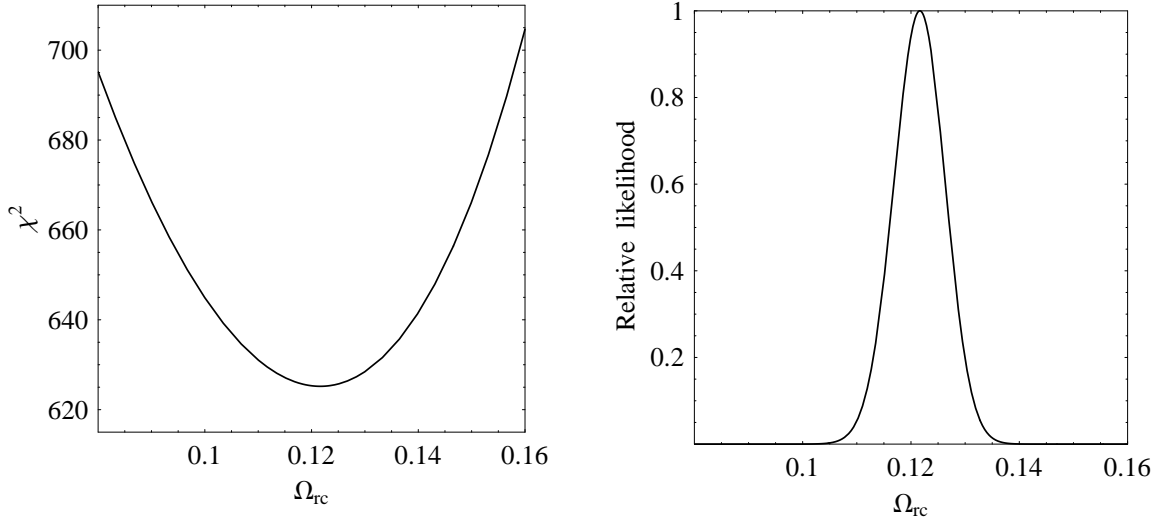


FIG. 7: The χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ as functions of Ω_{rc} for the DGP model.

C. Cosmological constraints on dark energy models

In this subsection, we consider the cosmological constraints on various dark energy models, by using the combined observations of the shift parameter R from the alternative CMB data of L&L [8], the latest Union2 SNIa dataset [20], and the distance parameter A [24] with n_s from L&L [8]. It is worth noting that the cosmological constraints on Λ CDM model, CPL model and HDE model have already been obtained in Secs. III A and III B. In the followings, we further consider the cosmological constraints on the other four dark energy models.

1. Λ CDM model

It is well known that in the spatially flat universe which contains pressureless matter and dark energy whose EoS is a constant w_x , the corresponding $E(z)$ is given by (see e.g. [59, 60])

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + (1-\Omega_{m0})(1+z)^{3(1+w_x)}}. \quad (23)$$

By minimizing the corresponding total $\chi^2 = \tilde{\chi}_\mu^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$, we find the best-fit parameters $\Omega_{m0} = 0.290$ and $w_x = -1.063$, while $\chi_{\text{min}}^2 = 543.45$. The corresponding $h = 0.700$ for the best fit. In Fig. 6, we present the corresponding 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - w_x$ parameter space for the Λ CDM model. Comparing with the corresponding results obtained in [59, 60], it is easy to find that Ω_{m0} becomes fairly larger, whereas w_x becomes slightly smaller.

2. DGP model

One of the simplest modified gravity models is the well-known Dvali-Gabadadze-Porrati (DGP) braneworld model [62, 63], which entails altering the Einstein-Hilbert action by a term arising from large extra dimensions. For a list of references on the DGP model, see e.g. [64, 65] and references therein. As is well known, for the spatially flat DGP model (here we only consider the self-accelerating branch), $E(z)$ is given by [63–65]

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + \Omega_{rc}} + \sqrt{\Omega_{rc}}, \quad (24)$$

where Ω_{rc} is a constant. It is easy to see that $E(z=0) = 1$ requires

$$\Omega_{m0} = 1 - 2\sqrt{\Omega_{rc}}. \quad (25)$$

Therefore, the DGP model has only one independent model parameter Ω_{rc} . Notice that $0 \leq \Omega_{rc} \leq 1/4$ is required by $0 \leq \Omega_{m0} \leq 1$. It is easy to obtain the total $\chi^2 = \tilde{\chi}_\mu^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$ as a function of the single model parameter Ω_{rc} . In Fig. 7, we plot the corresponding χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$. The best fit has $\chi_{\text{min}}^2 = 625.2$, whereas the best-fit parameter is $\Omega_{rc} = 0.122^{+0.005}_{-0.005}$ (with 1σ uncertainty) $^{+0.009}_{-0.010}$ (with 2σ uncertainty). The corresponding $h = 0.678$ for the best fit. From Eq. (25), $\Omega_{m0} = 0.302$ corresponds to the best-fit Ω_{rc} . Comparing with the corresponding results obtained in [59, 60], it is easy to find that Ω_{rc} becomes fairly smaller, and hence Ω_{m0} becomes fairly larger.

3. New agegraphic dark energy model

The so-called new agegraphic dark energy (NADE) model was proposed in [66, 67], based on the Károlyházy uncertainty relation which arises from quantum mechanics together with general relativity. In fact, the NADE model is an upgraded version of the agegraphic dark energy (ADE) model [68–70]. In the NADE model, the dark energy density is given by [66, 67]

$$\rho_q = \frac{3n^2 m_p^2}{\eta^2}, \quad (26)$$

where n is a constant of order unity; η is the conformal time which is defined by

$$\eta \equiv \int \frac{dt}{a} = \int \frac{da}{a^2 H}. \quad (27)$$

From the Friedmann equation $H^2 = (\rho_m + \rho_q) / (3m_p^2)$, the energy conservation equation $\dot{\rho}_m + 3H\rho_m = 0$, Eqs. (26) and (27), it is easy to find that the equation of motion for Ω_q , the fractional energy density of NADE, is given by [66, 67]

$$\frac{d\Omega_q}{dz} = -\Omega_q(1-\Omega_q) \left[3(1+z)^{-1} - \frac{2}{n} \sqrt{\Omega_q} \right]. \quad (28)$$

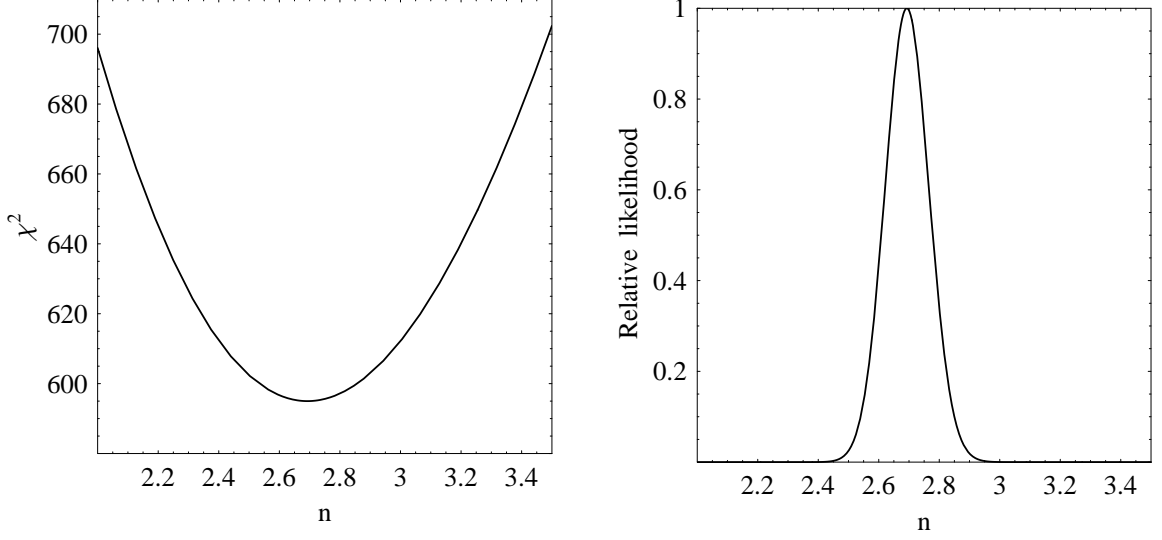


FIG. 8: The χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ as functions of n for the NADE model.

On the other hand, from the energy conservation equation $\dot{\rho}_q + 3H(\rho_q + p_q) = 0$, Eqs. (26) and (27), one can find that the EoS of NADE is given by [66, 67]

$$w_q \equiv \frac{p_q}{\rho_q} = -1 + \frac{2}{3n} \frac{\sqrt{\Omega_q}}{a}. \quad (29)$$

From Eqs. (26), (27) and (29), we have a very important result, namely, $\Omega_q = n^2 a^2 / 4$ in the matter-dominated epoch (we strongly refer to [66] for detailed arguments). Thanks to this special analytic feature $\Omega_q = n^2 a^2 / 4 = n^2 (1+z)^{-2} / 4$ in the matter-dominated epoch, NADE is a single-parameter model in practice. If n is given, we can obtain $\Omega_q(z)$ from Eq. (28) with the initial condition $\Omega_q(z_{ini}) = n^2 (1+z_{ini})^{-2} / 4$ at any z_{ini} which is deep enough into the matter-dominated epoch (we choose $z_{ini} = 2000$ as in [66]), instead of $\Omega_q(z=0) = 1 - \Omega_{m0}$ at $z=0$. Then, all other physical quantities, such as $\Omega_m(z) = 1 - \Omega_q(z)$ and $w_q(z)$ in Eq. (29), can be obtained correspondingly. So, $\Omega_{m0} = \Omega_m(z=0)$, $\Omega_{q0} = \Omega_q(z=0)$ and $w_{q0} = w_q(z=0)$ are *not* independent model parameters. The only free model parameter is n in the NADE model. From the Friedmann equation $H^2 = (\rho_m + \rho_q) / (3m_p^2)$, we have

$$E(z) = \left[\frac{\Omega_{m0}(1+z)^3}{1 - \Omega_q(z)} \right]^{1/2}. \quad (30)$$

If the single model parameter n is given, we can obtain $\Omega_q(z)$ from Eq. (28) with the initial condition $\Omega_q(z_{ini}) = n^2 (1+z_{ini})^{-2} / 4$ at z_{ini} . Thus, we get $\Omega_{m0} = 1 - \Omega_q(z=0)$. Then, $E(z)$ is on hand. Therefore, we can find the corresponding total $\chi^2 = \chi_\mu^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$. In Fig. 8, we plot the total χ^2 and likelihood $\mathcal{L} \propto e^{-\chi^2/2}$ as functions of n . The best fit has $\chi_{min}^2 = 595.001$, whereas the best-fit parameter is $n = 2.693^{+0.073}_{-0.072}$ (with 1σ uncertainty) $^{+0.146}_{-0.143}$ (with 2σ uncertainty). The corresponding $h = 0.681$ for the best fit. On the other hand, we find that $\Omega_{m0} = 0.299$, $\Omega_{q0} = 0.701$ and $w_{q0} = -0.793$ correspond to the best-fit n . Comparing with the corresponding results obtained in [59, 60, 71], we find that n becomes fairly smaller, and correspondingly Ω_{m0} becomes fairly larger.

4. Ricci dark energy model

The so-called Ricci dark energy (RDE) model was proposed in [72], which can be regarded as a variant of the HDE model mentioned above, while its corresponding cut-off L in Eq. (19) is chosen to be proportional

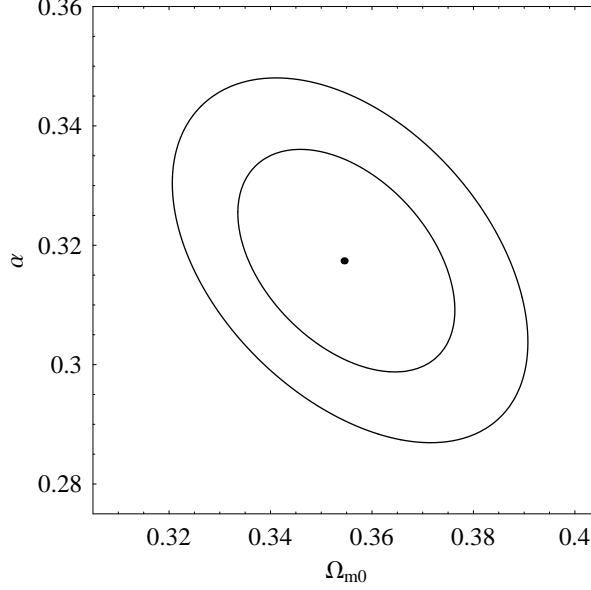


FIG. 9: The 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - \alpha$ parameter space for the RDE model. The best-fit parameters are also indicated by a black solid point.

to the Ricci scalar curvature radius. In [72], there is no physical motivation to this proposal for L in fact. Later, in [73] it is found that the Jeans length R_{CC} which is determined by $R_{CC}^{-2} = \dot{H} + 2H^2$ gives the causal connection scale of perturbations in the flat universe. Since the Ricci scalar is also proportional to $\dot{H} + 2H^2$ in the flat universe, the physical motivation for RDE has been found in [73] actually. In the RDE model, the corresponding ρ_Λ is given by [72]

$$\rho_\Lambda = 3\alpha m_p^2 (\dot{H} + 2H^2), \quad (31)$$

where α is a positive constant (when L is chosen to be R_{CC} in Eq. (19), one can see that $\alpha = c^2$ in fact). Substituting Eq. (31) into Friedmann equation, it is easy to find that [59, 60, 72]

$$E(z) = \left[\frac{2\Omega_{m0}}{2-\alpha} (1+z)^3 + \left(1 - \frac{2\Omega_{m0}}{2-\alpha} \right) (1+z)^{4-2/\alpha} \right]^{1/2}. \quad (32)$$

There are two independent model parameters, namely Ω_{m0} and α . By minimizing the corresponding total $\chi^2 = \tilde{\chi}_\mu^2 + \chi_{\text{CMB}}^2 + \chi_{\text{BAO}}^2$, we find the best-fit parameters $\Omega_{m0} = 0.355$ and $\alpha = 0.317$, while $\chi_{\text{min}}^2 = 588.303$. In Fig. 9, we present the corresponding 68.3% and 95.4% C.L. contours in the $\Omega_{m0} - \alpha$ parameter space for the RDE model. Comparing with the corresponding results obtained in [59, 60], it is easy to find that Ω_{m0} becomes fairly larger, whereas α becomes significantly smaller.

5. Comparison of dark energy models

In Table V, we summarize all the 7 dark energy models considered in this work. As mentioned above, it is common that L&L's alternative CMB data [8] favor a larger Ω_{m0} in all these dark energy models. Here we briefly consider the comparison of these models. Following [59, 60], we adopt three criteria used extensively in the literature, i.e., $\chi_{\text{min}}^2/\text{dof}$, Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC). Note that the degree of freedom $\text{dof} = N - k$, whereas N and k are the number of data points and the number of free model parameters, respectively. The BIC is defined by [74]

$$\text{BIC} = -2 \ln \mathcal{L}_{\text{max}} + k \ln N, \quad (33)$$

Model	Λ CDM	XCDM	CPL	DGP	NADE	HDE	RDE
Best fit	$\Omega_{m0} = 0.288$	$\Omega_{m0} = 0.290$ $w_x = -1.063$	$\Omega_{m0} = 0.288$ $w_0 = -0.969$ $w_a = -0.529$	$\Omega_{rc} = 0.122$	$n = 2.693$	$\Omega_{m0} = 0.298$ $c = 0.658$	$\Omega_{m0} = 0.355$ $\alpha = 0.317$
χ^2_{min}	545.239	543.45	542.936	625.2	595.001	546.628	588.303
k	1	2	3	1	1	2	2
χ^2_{min}/dof	0.977	0.976	0.977	1.120	1.066	0.981	1.056
ΔBIC	0	4.537	10.349	79.961	49.762	7.715	49.390
ΔAIC	0	0.211	1.697	79.961	49.762	3.389	45.064
Rank	1	2	3 \sim 4	7	5 \sim 6	3 \sim 4	5 \sim 6

TABLE V: Summarizing all the 7 dark energy models considered in this work.

where \mathcal{L}_{max} is the maximum likelihood. In the Gaussian cases, $\chi^2_{min} = -2 \ln \mathcal{L}_{max}$. So, the difference in BIC between two models is given by $\Delta BIC = \Delta \chi^2_{min} + \Delta k \ln N$. The AIC is defined by [75]

$$AIC = -2 \ln \mathcal{L}_{max} + 2k. \quad (34)$$

The difference in AIC between two models is given by $\Delta AIC = \Delta \chi^2_{min} + 2\Delta k$. In Table V, we present χ^2_{min}/dof , ΔBIC and ΔAIC for all the 7 models considered in this work. Notice that Λ CDM has been chosen to be the fiducial model when we calculate ΔBIC and ΔAIC . From Table V, it is easy to see that the rank of models is coincident in all the 3 criterions (χ^2_{min}/dof , BIC and AIC). The Λ CDM model is still the best, whereas the DGP model is still the worst. Comparing with the corresponding results obtained in [59, 60], we find that the rank of these models has only slight change. In other words, the influence to the rank from L&L's alternative CMB data [8] is fairly minor.

IV. CONCLUSION AND DISCUSSIONS

Recently, in a series of works by L&L [8–10], they claimed that there exists a timing asynchrony of -25.6 ms between the spacecraft attitude and radiometer output timestamps in the original raw WMAP time-ordered data (TOD). In [8], L&L reprocessed the WMAP data while the aforementioned timing asynchrony has been corrected, and they obtained an alternative CMB map in which the quadrupole dropped to nearly zero. In the present work, we try to see the implications to dark energy cosmology if L&L are right. While L&L claimed that there is a bug in the WMAP pipeline which leads to significantly different cosmological parameters, an interesting question naturally arises, namely, how robust is the current dark energy cosmology with respect to systematic errors and bugs? So, in this work, we adopt the alternative CMB data of L&L as a strawman to study the robustness of dark energy predictions.

In this work, we found that L&L's alternative CMB data [8] favor a larger Ω_{m0} in all the dark energy models. As a result, we found that the tension between CMB and SNIa can be alleviated to some extent, since SNIa dataset usually favors a large Ω_{m0} . However, the age problem becomes even worse in the dark energy models, since a larger Ω_{m0} usually leads to a smaller age of our universe at any redshift z . On the other hand, we found that L&L's alternative CMB data [8] do not significantly change the rank of dark energy models from the perspective of model comparison. Of course, it is a big advantage that the quadrupole dropped to nearly zero in the alternative CMB map of L&L (see [8–10]). Altogether, we consider that it is better to keep neutral to L&L's findings so far. While WMAP has been critical in establishing a highly successful cosmology, it is most important that these results are verified by other independent experiments, such as Planck.

Finally, we stress that this work is a hypothetical study in fact, since the works of L&L [8–10] are highly controversial in the community. One should be aware of the risk that the present work is likely to be completely irrelevant if it turns out that the works of L&L are indeed flawed. Here are some

remarks to be taken serious (we thank the anonymous referee for pointing out these issues). Firstly, in fact there are many discussions on L&L's claims in the community (see e.g. [77–79]), and many people (including both WMAP and Planck experts) believe that L&L are mistaken in their claims. Secondly, if the high- ℓ spectrum really is as discrepant as claimed by L&L, one could expect that many ground-based experiments would also have seen this effect. Thirdly, it is worth asking whether the timing offset was applied correctly in the actual map making but not in the calibration step. Up to now, to our knowledge, the discussions on L&L's claims in the community are still unsettled, whereas L&L are still defending their claims persistently in more papers (see [80] for instance) and in many conferential talks around the world. We hope that this ongoing controversy could be finished with a firm and reliable conclusion in the near future.

ACKNOWLEDGEMENTS

We thank the anonymous referee for quite expert comments and useful suggestions, which help us to improve this work. We would like to express our gratitude to Prof. Ti-Pei Li for his talk given in the period of the Annual Conference of Chinese Astronomical Society, Nanning, China, November 2010. We are grateful to Prof. Rong-Gen Cai and Prof. Shuang Nan Zhang for helpful discussions. We also thank Minzi Feng, as well as Xiao-Peng Ma and Hao-Yu Qi, for kind help and discussions. This work was supported in part by NSFC under Grant No. 10905005, the Excellent Young Scholars Research Fund of Beijing Institute of Technology, and the Fundamental Research Fund of Beijing Institute of Technology.

-
- [1] E. J. Copeland, M. Sami and S. Tsujikawa, *Int. J. Mod. Phys. D* **15**, 1753 (2006) [hep-th/0603057];
J. Frieman, M. Turner and D. Huterer, *Ann. Rev. Astron. Astrophys.* **46**, 385 (2008) [arXiv:0803.0982];
S. Tsujikawa, arXiv:1004.1493 [astro-ph.CO].
 - [2] A. G. Riess *et al.*, *Astron. J.* **116**, 1009 (1998) [astro-ph/9805201];
S. Perlmutter *et al.*, *Astrophys. J.* **517**, 565 (1999) [astro-ph/9812133].
 - [3] D. N. Spergel *et al.*, *Astrophys. J. Suppl.* **148**, 175 (2003) [astro-ph/0302209];
C. L. Bennett *et al.*, *Astrophys. J. Suppl.* **148**, 1 (2003) [astro-ph/0302207].
 - [4] K. Land and J. Magueijo, *Phys. Rev. Lett.* **95**, 071301 (2005) [astro-ph/0502237];
K. Land and J. Magueijo, *Mon. Not. Roy. Astron. Soc.* **378**, 153 (2007) [astro-ph/0611518].
 - [5] M. Demianski and A. G. Doroshkevich, *Phys. Rev. D* **75**, 123517 (2007) [astro-ph/0702381];
M. J. Longo, astro-ph/0703694;
A. Bernui and W. S. Hipolito-Ricaldi, *Mon. Not. Roy. Astron. Soc.* **389**, 1453 (2008) [arXiv:0807.1076];
L. P. He and Q. Guo, *Res. Astron. Astrophys.* **10**, 116 (2010) [arXiv:0912.1913];
A. Bernui, *Phys. Rev. D* **80**, 123010 (2009) [arXiv:0912.1147];
D. Wands, *Nature Phys.* **5**, 89 (2009);
L. Campanelli, *Phys. Rev. D* **80**, 063006 (2009) [arXiv:0907.3703];
X. Gao, arXiv:0903.1412 [astro-ph.CO];
R. Battye and A. Moss, *Phys. Rev. D* **80**, 023531 (2009) [arXiv:0905.3403].
 - [6] L. Campanelli, P. Cea and L. Tedesco, *Phys. Rev. Lett.* **97**, 131302 (2006) [astro-ph/0606266];
J. G. Cresswell *et al.*, *Phys. Rev. D* **73**, 041302 (2006) [astro-ph/0512017];
L. Campanelli, P. Cea and L. Tedesco, *Phys. Rev. D* **76**, 063007 (2007) [arXiv:0706.3802];
R. Holman, L. Mersini-Houghton and T. Takahashi, *Phys. Rev. D* **77**, 063511 (2008) [hep-th/0612142];
J. P. Luminet, arXiv:0802.2236 [astro-ph];
R. Aurich, S. Lustig, F. Steiner and H. Then, *Class. Quant. Grav.* **24**, 1879 (2007) [astro-ph/0612308];
L. R. Abramo and H. S. Xavier, *Phys. Rev. D* **75**, 101302 (2007) [astro-ph/0612193];
J. P. Luminet, arXiv:0704.3374 [astro-ph];
M. J. Reboucas and J. S. Alcaniz, *Braz. J. Phys.* **35**, 1062 (2005) [astro-ph/0604087];
W. S. Hipolito-Ricaldi and G. I. Gomero, *Phys. Rev. D* **72**, 103008 (2005) [astro-ph/0507238].
 - [7] H. Alnes and M. Amarzguoui, *Phys. Rev. D* **74**, 103520 (2006) [astro-ph/0607334];
S. Chang, M. Kleban and T. S. Levi, *JCAP* **0804**, 034 (2008) [arXiv:0712.2261];

- C. Dvorkin, H. V. Peiris and W. Hu, Phys. Rev. D **77**, 063008 (2008) [arXiv:0711.2321];
 J. A. Morales and D. Saez, arXiv:0802.1042 [astro-ph];
 D. C. Rodrigues, Phys. Rev. D **77**, 023534 (2008) [arXiv:0708.1168];
 J. Beltran Jimenez and A. L. Maroto, Phys. Rev. D **76**, 023003 (2007) [astro-ph/0703483];
 S. H. S. Alexander, Phys. Lett. B **660**, 444 (2008) [hep-th/0601034];
 T. R. Jaffe *et al.*, Astron. Astrophys. **460**, 393 (2006) [astro-ph/0606046];
 D. Boyanovsky, H. J. de Vega and N. G. Sanchez, Phys. Rev. D **74**, 123006 (2006) [astro-ph/0607508].
- [8] H. Liu and T. P. Li, arXiv:0907.2731 [astro-ph.CO].
 [9] H. Liu, S. L. Xiong and T. P. Li, arXiv:1003.1073 [astro-ph.CO];
 H. Liu and T. P. Li, Chin. Sci. Bull. **56**, 29 (2011) [arXiv:1005.2352];
 H. Liu, S. L. Xiong and T. P. Li, arXiv:1009.2701 [astro-ph.CO].
- [10] H. Liu and T. P. Li, arXiv:0806.4493 [astro-ph];
 H. Liu and T. P. Li, Sci. China **G52**, 804 (2009) [arXiv:0809.4160];
 T. P. Li *et al.*, Mon. Not. Roy. Astron. Soc. **398**, 47 (2009) [arXiv:0905.0075];
 H. Liu and T. P. Li, Sci. China **G53**, 567 (2010) [arXiv:0911.4063];
 H. Liu and T. P. Li, Chin. Sci. Bull. **55**, 907 (2010) [arXiv:1001.4643].
- [11] R. Aurich, S. Lustig and F. Steiner, Class. Quant. Grav. **27**, 095009 (2010) [arXiv:0903.3133].
 [12] B. F. Roukema, Astron. Astrophys. **518**, A34 (2010) [arXiv:1004.4506];
 B. F. Roukema, arXiv:1007.5307 [astro-ph.CO].
- [13] A. Moss, D. Scott and K. Sigurdson, JCAP **1101**, 001 (2011) [arXiv:1004.3995].
 [14] E. Komatsu *et al.*, Astrophys. J. Suppl. **180**, 330 (2009) [arXiv:0803.0547].
 [15] G. Hinshaw *et al.*, Astrophys. J. Suppl. **180**, 225 (2009) [arXiv:0803.0732].
 [16] Y. Wang and P. Mukherjee, Astrophys. J. **650**, 1 (2006) [astro-ph/0604051].
 [17] J. R. Bond, G. Efstathiou and M. Tegmark, Mon. Not. Roy. Astron. Soc. **291**, L33 (1997) [astro-ph/9702100].
 [18] W. Hu and N. Sugiyama, Astrophys. J. **471**, 542 (1996) [astro-ph/9510117].
 [19] H. Wei, N. N. Tang and S. N. Zhang, Phys. Rev. D **75**, 043009 (2007) [astro-ph/0612746].
 [20] R. Amanullah *et al.*, Astrophys. J. **716**, 712 (2010) [arXiv:1004.1711].
 The numerical data of the full Union2 sample are available at <http://supernova.lbl.gov/Union>
- [21] L. Perivolaropoulos, Phys. Rev. D **71**, 063503 (2005) [astro-ph/0412308].
 [22] E. Di Pietro and J. F. Claeskens, Mon. Not. Roy. Astron. Soc. **341**, 1299 (2003) [astro-ph/0207332].
 [23] M. Tegmark *et al.*, Phys. Rev. D **69**, 103501 (2004) [astro-ph/0310723];
 M. Tegmark *et al.*, Astrophys. J. **606**, 702 (2004) [astro-ph/0310725];
 U. Seljak *et al.*, Phys. Rev. D **71**, 103515 (2005) [astro-ph/0407372];
 M. Tegmark *et al.*, Phys. Rev. D **74**, 123507 (2006) [astro-ph/0608632].
- [24] D. J. Eisenstein *et al.*, Astrophys. J. **633**, 560 (2005) [astro-ph/0501171].
 [25] S. Nesseris and L. Perivolaropoulos, Phys. Rev. D **70**, 043531 (2004) [astro-ph/0401556].
 [26] H. Wei, Phys. Lett. B **691**, 173 (2010) [arXiv:1004.0492];
 H. Wei, Phys. Lett. B **692**, 167 (2010) [arXiv:1005.1445];
 H. Wei, arXiv:1010.1074 [gr-qc];
 H. Wei, Eur. Phys. J. C **62**, 579 (2009) [arXiv:0812.4489].
- [27] H. K. Jassal, J. S. Bagla and T. Padmanabhan, Phys. Rev. D **72**, 103503 (2005) [astro-ph/0506748];
 H. K. Jassal, J. S. Bagla and T. Padmanabhan, astro-ph/0601389.
- [28] S. Nesseris and L. Perivolaropoulos, Phys. Rev. D **72**, 123519 (2005) [astro-ph/0511040].
 [29] A. G. Riess *et al.*, Astrophys. J. **607**, 665 (2004) [astro-ph/0402512].
 [30] P. Astier *et al.*, Astron. Astrophys. **447**, 31 (2006) [astro-ph/0510447].
 [31] A. G. Riess *et al.*, Astrophys. J. **659**, 98 (2007) [astro-ph/0611572].
 [32] S. Nesseris and L. Perivolaropoulos, JCAP **0702**, 025 (2007) [astro-ph/0612653].
 [33] M. Kowalski *et al.*, Astrophys. J. **686**, 749 (2008) [arXiv:0804.4142].
 [34] M. Hicken *et al.*, Astrophys. J. **700**, 1097 (2009) [arXiv:0901.4804].
 [35] H. Wei, Phys. Lett. B **687**, 286 (2010) [arXiv:0906.0828].
 [36] G. R. Bengochea, Phys. Lett. B **696**, 5 (2011) [arXiv:1010.4014].
 [37] Z. X. Li, P. X. Wu and H. W. Yu, Phys. Lett. B **695**, 1 (2011) [arXiv:1011.1982].
 [38] M. Chevallier and D. Polarski, Int. J. Mod. Phys. D **10**, 213 (2001) [gr-qc/0009008];
 E. V. Linder, Phys. Rev. Lett. **90**, 091301 (2003) [astro-ph/0208512].
 [39] S. Nesseris and L. Perivolaropoulos, Phys. Rev. D **70**, 043531 (2004) [astro-ph/0401556].

- [40] R. Lazkoz, S. Nesseris and L. Perivolaropoulos, JCAP **0511**, 010 (2005) [astro-ph/0503230].
- [41] Y. G. Gong, B. Wang and R. G. Cai, JCAP **1004**, 019 (2010) [arXiv:1001.0807].
- [42] J. S. Alcaniz and J. A. S. Lima, Astrophys. J. **521**, L87 (1999) [astro-ph/9902298].
- [43] J. Dunlop *et al.*, Nature **381**, 581 (1996);
H. Spinrad *et al.*, Astrophys. J. **484**, 581 (1997).
- [44] J. Dunlop, in *The Most Distant Radio Galaxies*, edited by H. J. A. Rottgering, P. Best and M. D. Lehnert, Kluwer, Dordrecht (1999), page 71.
- [45] A. Stockton, M. Kellogg and S. E. Ridgway, Astrophys. J. **443**, L69 (1995).
- [46] Y. Yoshii, T. Tsujimoto and K. Kawara, Astrophys. J. **507**, L113 (1998) [astro-ph/9809047].
- [47] G. Hasinger, N. Schartel and S. Komossa, Astrophys. J. **573**, L77 (2002) [astro-ph/0207005].
- [48] S. Komossa and G. Hasinger, astro-ph/0207321.
- [49] A. Friaca, J. Alcaniz and J. A. S. Lima, Mon. Not. Roy. Astron. Soc. **362**, 1295 (2005) [astro-ph/0504031].
- [50] D. Jain and A. Dev, Phys. Lett. B **633**, 436 (2006) [astro-ph/0509212].
- [51] J. S. Alcaniz, J. A. S. Lima and J. V. Cunha, Mon. Not. Roy. Astron. Soc. **340**, L39 (2003) [astro-ph/0301226].
- [52] J. A. S. Lima and J. S. Alcaniz, Mon. Not. Roy. Astron. Soc. **317**, 893 (2000) [astro-ph/0005441].
- [53] R. J. Yang and S. N. Zhang, Mon. Not. Roy. Astron. Soc. **407**, 1835 (2010) [arXiv:0905.2683].
- [54] H. Wei and S. N. Zhang, Phys. Rev. D **76**, 063003 (2007) [arXiv:0707.2129].
- [55] S. Wang, X. D. Li and M. Li, Phys. Rev. D **82**, 103006 (2010) [arXiv:1005.4345].
- [56] A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Rev. Lett. **82**, 4971 (1999) [hep-th/9803132];
S. D. H. Hsu, Phys. Lett. B **594**, 13 (2004) [hep-th/0403052].
- [57] M. Li, Phys. Lett. B **603**, 1 (2004) [hep-th/0403127].
- [58] G. 't Hooft, gr-qc/9310026;
L. Susskind, J. Math. Phys. **36**, 6377 (1995) [hep-th/9409089];
R. Bousso, Rev. Mod. Phys. **74**, 825 (2002) [hep-th/0203101].
- [59] H. Wei, JCAP **1008**, 020 (2010) [arXiv:1004.4951].
- [60] M. Li, X. D. Li and X. Zhang, Sci. China Phys. Mech. Astron. **53**, 1631 (2010) [arXiv:0912.3988].
- [61] X. Zhang and F. Q. Wu, Phys. Rev. D **76**, 023502 (2007) [astro-ph/0701405].
- [62] G. R. Dvali, G. Gabadadze and M. Porrati, Phys. Lett. B **485**, 208 (2000) [hep-th/0005016].
- [63] C. Deffayet, Phys. Lett. B **502**, 199 (2001) [hep-th/0010186];
C. Deffayet, G. R. Dvali and G. Gabadadze, Phys. Rev. D **65**, 044023 (2002) [astro-ph/0105068].
- [64] H. Wei, Phys. Lett. B **664**, 1 (2008) [arXiv:0802.4122].
- [65] A. Lue, Phys. Rept. **423**, 1 (2006) [astro-ph/0510068].
- [66] H. Wei and R. G. Cai, Phys. Lett. B **663**, 1 (2008) [arXiv:0708.1894].
- [67] H. Wei and R. G. Cai, Phys. Lett. B **660**, 113 (2008) [arXiv:0708.0884].
- [68] R. G. Cai, Phys. Lett. B **657**, 228 (2007) [arXiv:0707.4049].
- [69] H. Wei and R. G. Cai, Eur. Phys. J. C **59**, 99 (2009) [arXiv:0707.4052];
H. Wei and R. G. Cai, Phys. Lett. B **655**, 1 (2007) [arXiv:0707.4526].
- [70] X. Wu, Y. Zhang, H. Li, R. G. Cai and Z. H. Zhu, arXiv:0708.0349 [astro-ph];
Y. Zhang, H. Li, X. Wu, H. Wei and R. G. Cai, arXiv:0708.1214 [astro-ph];
X. Zhang, J. Zhang and H. Liu, Eur. Phys. J. C **54**, 303 (2008) [arXiv:0801.2809].
- [71] H. Wei, Eur. Phys. J. C **60**, 449 (2009) [arXiv:0809.0057].
- [72] C. J. Gao, F. Q. Wu, X. L. Chen and Y. G. Shen, Phys. Rev. D **79**, 043511 (2009) [arXiv:0712.1394].
- [73] R. G. Cai, B. Hu and Y. Zhang, Commun. Theor. Phys. **51**, 954 (2009) [arXiv:0812.4504].
- [74] G. Schwarz, Ann. Stat. **6**, 461 (1978).
- [75] H. Akaike, IEEE Trans. Automatic Control **19**, 716 (1974).
- [76] Y. F. Cai, E. N. Saridakis, M. R. Setare and J. Q. Xia, Phys. Rept. **493**, 1 (2010) [arXiv:0909.2776].
- [77] <http://cosmocooffee.info/viewtopic.php?t=1395>
- [78] <http://cosmocooffee.info/viewtopic.php?t=1537>
- [79] <http://forums.randi.org/archive/index.php/t-169137.html> (see comment by Tim Thompson, JPL)
- [80] H. Liu and T. P. Li, arXiv:1101.2720 [astro-ph.CO].